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# Daytime Solar Heating of Photovoltaic Arrays in Low Density Plasmas

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## Abstract

The purpose of the current work is to determine the out-gassing rate of H<sub>2</sub>O molecules for a solar array placed under daytime solar heating (full sunlight) conditions typically encountered in a Low Earth Orbital (LEO) environment. Arc rates are established for individual arrays held at 14 °C and are used as a baseline for future comparisons. Radiated thermal solar flux incident to the array is simulated by mounting a stainless steel panel equipped with resistive heating elements several centimeters behind the array. A thermal plot of the heater plate temperature and the array temperature as a function of heating time is then obtained. A mass spectrometer is used to record the levels of partial pressure of water vapor in the test chamber after each of the 5 heating / cooling cycles. Each of the heating cycles was set to time duration of 40 minutes to simulate the daytime solar heat flux to the array over a single orbit. Finally the array is cooled back to ambient temperature after 5 complete cycles and the arc rates of the solar arrays is retested. A comparison of the various data is presented with rather some unexpected results.

## Nomenclature

$n$	molecular number density, m <sup>-3</sup>
$S, S_a$	surface area, m <sup>2</sup>
$\Gamma$	flux, # molecules·m <sup>-2</sup> ·s <sup>-1</sup>
$R_{out}$	out gassing rate, molecules · s <sup>-1</sup>
$m$	mass, kg
$P$	pressure, Pa
$\overline{v^2}$	root-mean square of velocity, m <sup>2</sup> ·s <sup>-2</sup>
$I_w$	wire current, A
$R_L$	load resistance, ohms
$K$	Boltzmann constant, J · K <sup>-1</sup>
$\sigma$	Stefan-Boltzmann const., W · m <sup>-2</sup> · K <sup>-4</sup>
$P_{tot}$	Total output power, W
$Q$	radiated power, W
$C$	heat capacity, J/K
$C_m$	specific heat, W/kg · K
$T$	temperature, K
$t$	time, s

## Introduction

We have observed on numerous occasions in ground chamber tests that conventional silicon solar arrays begin to instantaneously arc when the full negative bias voltage is first applied to the array.<sup>1,2</sup> Indeed as many as 100 arcs or more arcs have been observed in the first few seconds after a large negative bias has been supplied to the solar array. In order to preserve the integrity of the array it often becomes necessary to back off the bias potential to a point just below the arcing threshold

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where no arcs occur before proceeding to determine the overall arcing rate for the solar array. In principal the arcing process for a particular array depends on a number of factors. For example solar array design and composition, small scale manufacturing defects and or protrusions caused by non-uniformity of the exposed contacts in adjoining photovoltaic cells as well as arc conditioning of solar array contacts all play a significant role in the arc initiation process. Furthermore plasma density at a given bias voltage also influences the arcing rate of individual strings on an array.

Most arcs tend to occur at the metal-dielectric and plasma junctions (termed triple junction sites) on a solar array<sup>3-5</sup> However, it is also interesting to note that more than 30 percent of all recorded arcs are caused by arcs occurring at the edge of the un-insulated photovoltaic cells on the solar array. Moreover, previous experimental tests have shown that arcs on solar array are caused by a desorbed gas ionization mechanism<sup>6</sup> Past optical spectroscopy experiments,<sup>7,8</sup> coupled with more recent mass spectrometer measurements<sup>9</sup> have confirmed that condensed water vapor molecules residing at the triple junction sites are responsible for solar array arc initiation.

### **Solar Array Thermal Balance**

In situ measurements of the maximum output power  $P_{max} = 1000$  W and the maximum current  $I_{max} = 9.1$  amperes supplied from a Variac under full resistive load conditions  $R_L = 9.8 \Omega$  were first obtained. The total output power in watts is given by

$$P_{tot}(I_w) = I_w^2 \cdot R_L \quad (1)$$

Where  $P_{tot}(I_w)$  is the total output power of the heater plate and  $I_w$  is the current. A plot of the radiated power is given in figure (1).

The thermal heat capacity of the solar array sample is given by equation (2).

$$C = \left. \frac{dQ}{dT} \right|_{sample} \quad (2)$$

where  $Q$  is the radiated power given by the Stephan-Boltzmann law in equation (3) and  $S = 0.46 \text{ m}^2$  is the area of the heater plate. Assuming  $T_0$  is the temperature of the heater plate and  $T_1$  represents the temperature of the solar array sample we have

$$Q(T) = S \cdot \sigma \cdot T_0^4 - 2 \cdot \sigma \cdot T_1^4 \quad (3)$$

Note that the factor of  $-2$  in equation (3) comes from the fact that the array sample radiates heat from both sides of the solar array. The specific heat is defined as the heat capacity,  $C_p(T)$  per unit mass of a substance and is written as

$$C_m = \frac{C}{m_{sample} + fiberglass + \dots} \quad (4)$$

The transfer of heat (or heat conduction from  $T_0$  to  $T_1$ ) to the solar array across a fiberglass plate of thickness  $d$  in time  $t$  can be written as

$$C_m \cdot \rho \cdot d \cdot \frac{dT_1}{dt} = a \cdot \sigma \cdot c \cdot T_0^4 - 2 \cdot \sigma \cdot c \cdot T_1^4 \quad (5)$$

The above equation can be rewritten in the following form

$$\frac{dT_1}{dt} = \frac{a \cdot \sigma \cdot c \cdot T_0^4}{c_m \cdot \rho \cdot d} - \frac{2 \cdot \sigma \cdot c \cdot T_1^4}{c_m \cdot \rho \cdot d} \quad (6)$$

We need to rewrite the above equation in dimensionless units of  $\tau$ .

$$\tau = \frac{T_1}{T_0} \quad (7)$$

Dividing both sides of equation (6) by  $T_0$  and making use of equation (7) yields the following expression

$$\frac{d\tau}{dt} = \frac{a \cdot \sigma \cdot c \cdot T_0^3}{c_m \cdot \rho \cdot d} - \frac{2 \cdot \sigma \cdot c \cdot T_0^3}{c_m \cdot \rho \cdot d} \cdot \tau^4 \quad (8)$$

Separating out the variables and, integrating both sides of equation (8) results in

$$\int_0^t dt = \frac{2 \cdot \sigma \cdot c \cdot T_0^3}{c_m \cdot \rho \cdot d} \cdot \int_{\tau_0}^{\tau_1} \frac{d\tau}{0.5a - \tau^4}$$

where we estimate that (9)

$$\frac{2 \cdot \sigma \cdot c \cdot T_0^3}{c_m \cdot \rho \cdot d} \cong 10^3 \rightarrow 10^4 \text{ sec.}$$

Carrying out the integration on the right hand side of equation (9) yields

$$\int_{\tau_0}^{\tau_1} \frac{d\tau}{0.5a - \tau^4} = \xi(\tau) \quad (10)$$

where

$$\xi(\tau) = \frac{1}{4 \cdot a^{\frac{3}{4}}} \cdot \left[ \ln \left[ \frac{\tau + \sqrt[4]{a}}{\tau - \sqrt[4]{a}} \right] + 2 \cdot \tan^{-1} \left[ \frac{\tau}{\sqrt[4]{a}} \right] \right]$$

Combining equations (9) and (10) it is possible to write

$$t = 10^4 \cdot \xi(\tau) \quad (11)$$

Where:  $0 < a < 1$ . Setting  $a = 0.5$  and assuming the initial boundary conditions: at  $t = 0$ ,  $\tau_0 = 0.75$ . Figure 2 shows a plot of equation (11). The radiant power available to heat the solar array is about 0.8 of the maximum power radiated by the heater. Experimental plots of the thermocouple

temperatures for the solar array and the heater plate are shown in figure 3.

### Experimental Apparatus

All tests were performed in the large vertical chamber at the NASA Glenn Research Center Plasma Interaction Facility (PIF) shown in figure 4. A “Kaufman type” discharge chamber equipped with a hot wire filament was used to produce xenon plasma for the experiment. The plasma source adequately simulates the plasma densities encountered in a LEO environment. A base pressure of  $9.99 \times 10^{-5}$  Pa was established before introducing xenon gas neutrals to the vacuum chamber. High purity gaseous xenon was slowly bled in the source using a carefully controlled leak valve. Vacuum tank pressure was monitored via an ionization gauge. A neutral gas background pressure of  $5.33 \times 10^{-3}$  Pa ( $4.0 \times 10^{-5}$  Torr) was maintained for all tests before turning on the source and commencing with the plasma production. Two spherical langmuir probes were used to obtain the basic plasma parameters as well as to monitor the degree of ionization of the plasma. An electron temperature of 1.7 eV and a number density of  $4.5 \times 10^5 \text{ cm}^{-3}$  were maintained throughout the tests. A mass spectrometer was used to record the levels of partial pressure of  $\text{H}_2\text{O}$  vapor in the vacuum system before and after each heating/cooling cycle.

The solar arrays supplied from the manufacturer were mounted on an insulated fiberglass backing material equipped with mounting holes at each corner (see figure 5). Each solar array has 3 individual strings consisting of 12 cells per string with all cells wired in series. The array strings were positioned side by side with an insulating RTV layer applied between each of the adjacent strings on the array. Individual cells were composed of conventional 6 cm by 9 cm silicon solar cells each developing an output potential of 0.5 volts at 20 milliamps

of current under 1 full sun. The output of each array string was directly tied to a single RG-59 coaxial cable terminated with a BNC connector. A total of 3 coaxial cables (one cable for each array string) were connected to each solar array. All wire connections were tested for continuity, insulated with kapton tape and washed with acetone prior to mounting them on the heater plate assembly. A second array panel was also prepared in the same manner.

Next a 76 cm high × 61 cm wide plate was cut from ¼ inch aluminum stock. Two 120V AC resistive heater elements were attached to one side of the plate. Power was supplied to the resistive load using a Variac power supply. Holes were drilled into the plate and four 7.6 cm high ceramic standoff cylinders were attached. The two solar array panels were then mounted to the ceramic standoffs and the entire array and heater panel assembly were hung in the tank. (see figure 5). Finally two “type T” thermocouples was attached (one the heater plate assembly and a second attached to the solar array). The 6 coaxial cables from the solar array panels were next connected to the electrical feed through port located on the side of the vacuum chamber wall. Outside the chamber each of the string cables were attached to a BNC cable patch network. The three strings of each solar array were then connected in parallel so that the full array could be biased.

Other miscellaneous equipment included a mass spectrometer, current and voltage sources (needed to power the plasma source), two programmable source and measure units (used for biasing the solar arrays and monitoring the plasma density), a current probe, voltage probe and, a 4 channel 2 GHz digital storage scope. Finally an analog to digital card and data acquisition software were installed on a microcomputer. See figure 6 for details concerning the R-C circuit and hardware used in detecting arcs on a solar array.

## **Test Results**

A number of systematic measurements were tailored to simulate the on orbit daytime solar heating conditions that would be encountered by a solar array placed in a LEO environment. A maximum of five orbits (each orbit being about 40 minutes in duration) has been simulated by thermal cycling the array to a temperature of approximately 80 °C. The array is held at 80 °C for a duration of 40 minutes before the array is allowed to be cooled back down to the ambient temperature. The partial pressure of H<sub>2</sub>O vapor in the chamber was measured by the mass spectrometer at least once during each thermal cycle. The array is allowed to cool back down to the ambient temperature and the partial pressure of water vapor is recorded before the proceeding to the next thermal cycle.

As a baseline measurement both the partial pressure and the arc rates were initially determined before thermal cycling the array. Figure 7 depicts the relative concentration of various species before any thermal cycling with the array at 14 °C and the tank pressure at  $5.33 \times 10^{-3}$  Pa. Figure 8 shows a snapshot taken with the mass spectrometer after 5 complete thermal cycles with the array at 14 °C. Table A quantifies the mass spectrometer results in numerical form. The results in Table A show a 3.4 times reduction in the total pressure after 5 complete thermal cycles. Note that the

**Table A**

(Summary of partial pressures for several species after 5 thermal cycles)

Species:	Before Thermal Cycling: (Pressure in Pa)	After 5 thermal Cycles: (Pressure in Pa)	Reduction
H	8.95E-08	3.43E-08	2.6
CH	7.14E-08	5.52E-08	1.3
O	8.97E-07	4.02E-07	2.2
OH	1.33E-06	3.83E-07	3.5
H <sub>2</sub> O	1.38E-06	4.02E-07	3.4
Oil	1.45E-06	8.04E-07	1.8
NO	3.56E-07	1.94E-07	1.8
hydrocarbons	1.45E-07	8.66E-08	1.7
Total Pressure	1.74E-06	5.10E-07	3.4



relative concentrations of OH and H<sub>2</sub>O drop at nearly the same reduction factor as the total pressure. All measurements in table A were obtained only after the array was allowed to cool back down to the ambient temperature. Figure 9 plots the partial pressure of H<sub>2</sub>O in the vacuum chamber obtained after each thermal cycle.

It is a strongly held contention that H<sub>2</sub>O molecules residing at the triple junction sites (interconnects) of a solar array are both a necessary and sufficient condition for arcing onset. The arcing criterion is used to test the hypothesis of degassed water vapor loss due to solar heating. We proceeded to measure the arc rates after 5 complete thermal cycles with the plasma source operating, tank pressure at  $5.33 \times 10^{-3}$  Pa, and the array temperature at 14 °C. Table B summarizes the recorded arc rates that were measured before and after 5 complete thermal cycles.

**Table B**

(Summary of solar array arcing rates before and after thermal cycling)

Bias Voltage:	Before Thermal Cycling: (3 strings in parallel, C = 0.01 μF)	After 5 thermal Cycles: (3 strings in parallel, C = 0.01 μF)
- 280 V	20 arcs in 30 minutes	15 arcs in 30 minutes
- 300 V	28 arcs in 30 minutes	24 arcs in 30 minutes
- 320 V	26 arcs in 30 minutes	26 arcs in 30 minutes

In a separate test, with the plasma source off, xenon gas flow to the chamber was cut by closing an in line check valve. The diffusion pumps were then allowed to pump on the chamber in order to gain some incite into how water is affected by the tank pumping speed. The test was conducted with no array heating and with the array held at an ambient temperature of 20° C. Figure 10 clearly demonstrates how the relative concentration of water molecules drops after some 300 hours in the vacuum system. Direct mass spectrometer measurements have confirmed a 22 times reduction in the partial pressure of water vapor after 300 hours of pumping with no heating.

## Out-Gassing Rate Calculations

A single molecule incident on an inside surface of an enclosed volume will impart a total impulse or pressure proportional to the kinetic energy,  $E_k$ . Multiplying the kinetic energy of a single molecule by the number of molecules,  $n$ , enclosed in the volume yields the absolute pressure,  $P$ .

$$P = n \cdot \frac{2}{3} \cdot E_k \quad (12)$$

Where that  $n$  is the molecular number density per cubic meter and  $m = 18 \cdot m_p$  (the mass of the H<sub>2</sub>O molecule times the rest mass of the proton  $m_p$ ). The kinetic energy of a single molecule  $E_k$  is proportional to its temperature,  $T$  in degrees Kelvin.

$$E_k = \frac{1}{2} \cdot m \cdot \overline{v^2} = \frac{3}{2} \cdot K \cdot T \quad (13)$$

The mean thermal velocity calculated by Maxwell and Boltzmann is given by

$$\overline{v} = \sqrt{\frac{8 \cdot K \cdot T}{\pi \cdot m}} \quad (14)$$

Where  $\overline{v}$  is given in units of meters per second. Using equations (12 and 13) the absolute pressure  $P$  can be written as

$$P = n \cdot m \cdot \overline{v^2} = n \cdot K \cdot T \quad (15)$$

Note  $n$  is the number of molecules per cubic meter at an absolute pressure  $P$ . The pressure  $P$  is given in units of pascals.  $K$  is the Boltzmann constant. Solving for  $n$  in equation (15) yields:

$$n = \frac{P}{K \cdot T} \quad (16)$$

The number of H<sub>2</sub>O molecules crossing a

unit area in space per second is given by the flux,  $\Gamma$ . The flux is given by

$$\Gamma = \frac{n \cdot \bar{v}}{4} \quad (17)$$

Multiplying the flux  $\Gamma$  by the area of the array  $S_a$ , the out-gassing rate of  $H_2O$  molecules from the surface can be estimated from equation (18).

$$R_{out} = S_a \cdot \frac{n \cdot \bar{v}}{4} \quad (18)$$

Where  $R_{out}$  has units of the number of molecules per second and  $S_a = 0.173 \text{ m}^2$  represents the combined area of both arrays. Table C tabulates the out-gassing rate of water vapor molecules during each thermal cycle, as well as the result for a 300 hour test in the vacuum at 20 °C with no thermal cycling. For comparison purposes Table C also tabulates the calculated out-gassing rate of water molecules evaporated from the surface of the solar array for a 220 km altitude orbit in space which is heated to temperature of 80 °C by the sun.

Table C

(Summary of outgassing rates for water vapor molecules under various circumstances)

Circumstance:	P (pa)	T (°K)	n (mol · m <sup>-2</sup> )	$\bar{v}$ (m · s <sup>-1</sup> )	R <sub>out</sub> (mol · s <sup>-1</sup> )
during 1 <sup>st</sup> thermal cycle	3.44E-03	337	7.39E+17	627.27	2.00E+19
during 2 <sup>nd</sup> thermal cycle	2.00E-02	348	4.14E+18	637.42	1.14E+20
during 3 <sup>rd</sup> thermal cycle	4.91E-03	347	1.02E+18	636.51	2.82E+19
during 4 <sup>th</sup> thermal cycle	4.12E-03	345	8.65E+17	634.67	2.37E+19
during 5 <sup>th</sup> thermal cycle	1.00E-02	350	2.81E+18	639.25	7.77E+19
300 hours pumping in vacuum chamber, no thermal cycling	1.24E-03	293	3.06E+17	584.89	7.74E+18
220km low earth orbit	1.33E-05	353	2.74E+15	641.98	7.59E+16

## Summary

The rate of loss of  $H_2O$  molecules from a surface depends largely on temperature, pressure and molecular number density. For a (180–300)km orbit (Space Shuttle orbiter) the absolute pressure is ranges from 6.68E-05 Pa to 1.68E-06 Pa (or 5.01E-07 Torr to 1.26E-08 Torr). The base pressure of the

vacuum chamber clearly puts us within the (180–300)km altitude range. Temperature ranges from +80 °C in full sunlight to –80°C to –100 °C during eclipse at these altitudes. Assuming a 220 km orbit (corresponding to an absolute pressure  $P = 1.33 \times 10^{-5}$  Pa ( $10^{-7}$  Torr) and an array temperature  $T = 353 \text{ K}$  (80 °C), it possible to calculate an over all out-gassing rate  $R_{out}$  in space. Our best estimate for the out-gassing rate of water molecules from the surface of an array situated in a 220 km orbit at 80 °C is 7.59E+16 molecules per second (see table C for details). Note that the over all out-gassing rate in space differs by 2 to 3 orders of magnitude from the out-gassing rates in the chamber during thermal cycling. The main reason for the large disparity in the out-gassing rate between space and the vacuum chamber arises from the difference in pressure. Because the vacuum chamber is a confined space of constant volume a rise in temperature results in a rise in pressure and molecular number density.

It has been hypothesized that  $H_2O$  molecules residing at the triple junction sites (interconnects) of a solar array establish both a necessary and sufficient condition for arcing onset in solar arrays. The arcing criterion has therefore been used to test the hypothesis of degassed water vapor loss due to solar heating. However, results for the tests were inconclusive. While there is a slight reduction in arcing rate (after 5 thermal cycles) at the –280 V and –300 V bias levels, there is virtually no change in the measured arc rate at a bias level of –320 V.

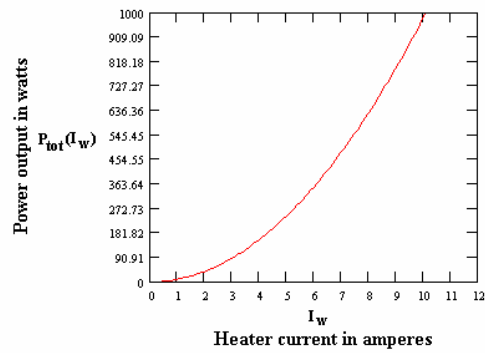
Current ground chamber arcing experiments conducted at the NASA Glenn Plasma Interaction Facility attempt to simulate the electrical conditions encountered by a spacecraft in orbit by simulating electron number densities, not the absolute pressure. Subsequently prior to doing the arc rate tests we first need to establish xenon plasma in the vacuum chamber. Note that the single largest contribution to the absolute pressure in the

chamber is due to the abundance of xenon gas. With xenon gas flowing and the plasma source operating we can do no better in pressure than  $1.33\text{E-}03$  Pa ( $10^{-5}$  Torr) while keeping electron number densities within acceptable limits.

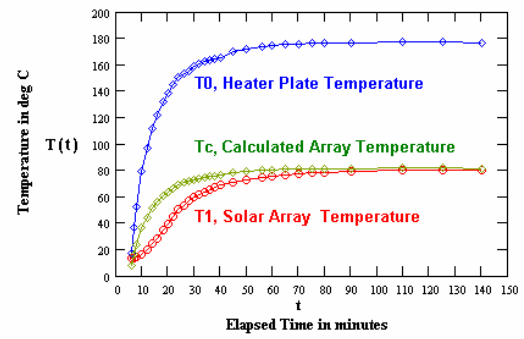
The vacuum chamber is a closed loop system. Water vapor driven out of the array by heating is absorbed by the diffusion pumps. The remaining water vapor in the plasma re-condenses on the surfaces of the of the solar array and chamber wall as soon as the array is cooled. This is not the case for a solar array out-gassing in space. (Water molecules removed by heating would continue to move away from the array expanding into space at a speed equal the mean thermal velocity.) What this ultimately means is that it is simply not possible to pump on Xenon,  $\text{H}_2\text{O}$  vapor, oil and all other mass species in the chamber to better than  $10^{-5}$  Torr. Water is removed from the chamber at much slower rate than would be the case without xenon gas flowing. As a result the diffusion pumps were unable remove enough water vapor from the chamber to effectively test the arcing criterion with any degree of certainty.

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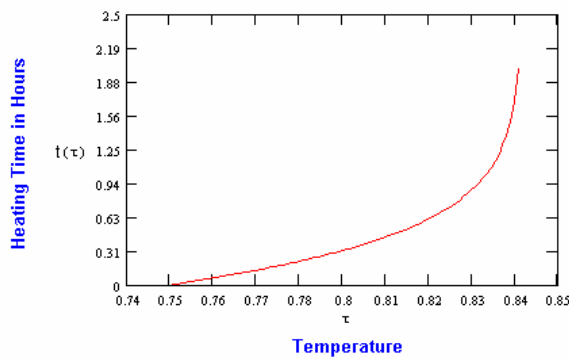


**Figure 1: Total power output from variac as a function of heater current**

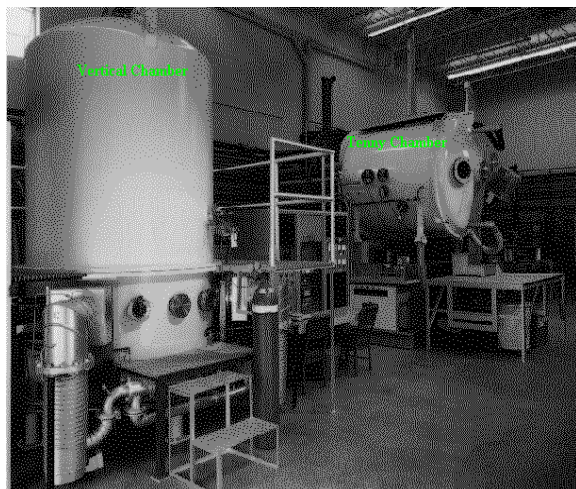


$$T_c(t) = \tau \cdot [T_0(t)], \text{ where: } \tau = \frac{T_1}{T_0} = \frac{80^\circ\text{C}}{173^\circ\text{C}} = 0.462$$

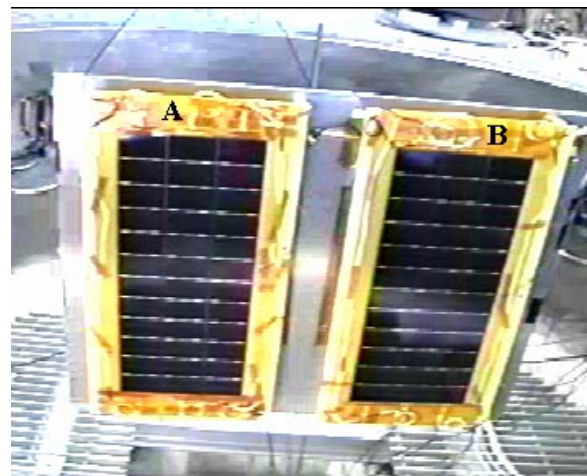
**Figure 2: Thermocouple temperature plots for heater plate and solar array. Array temperature is about half of the heater plate temperature.**



**Figure 3: Thermal balance of Tecstar solar pannels. Heating time 0.5-1 hours. Power to array is 0.8 max heater power**



**Figure 4: NASA Glenn Plasma Interaction Facility showing the 2x3 meter Vertical Chamber and the 1.5 x 2 meter Tenny Chamber**



**Figure 5: Solar arrays mounted to heater plate assembly with ceramic tube spacers.**

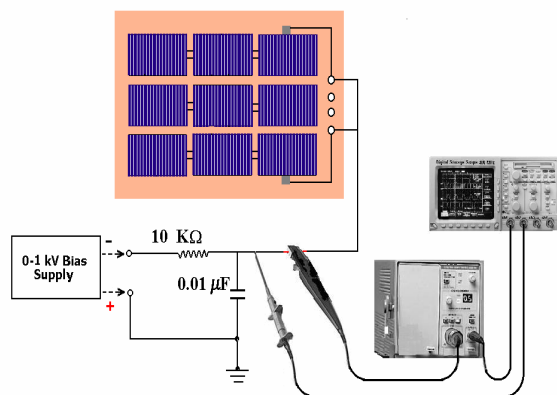


Figure 6: R-C circuit and hardware used for detecting arcs on solar arrays.

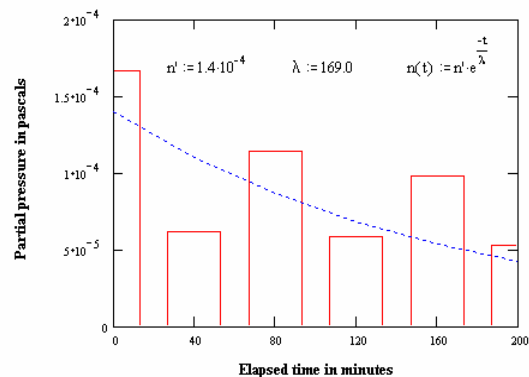


Figure 9: Partial pressure of water vapor after 5 complete 40 minute thermal cycles. Temperature at 14° C.

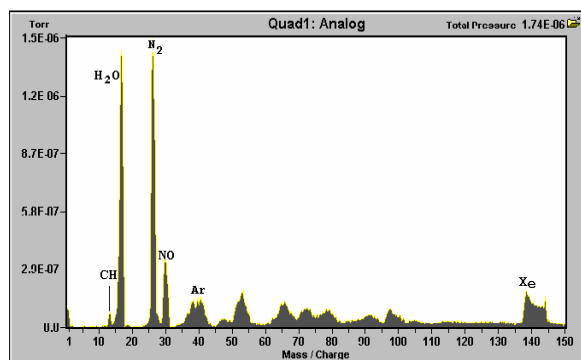


Figure 7: Background trace showing the partial pressure of several mass species before any thermal cycling. Trace was obtained with array temperature at 14° C.

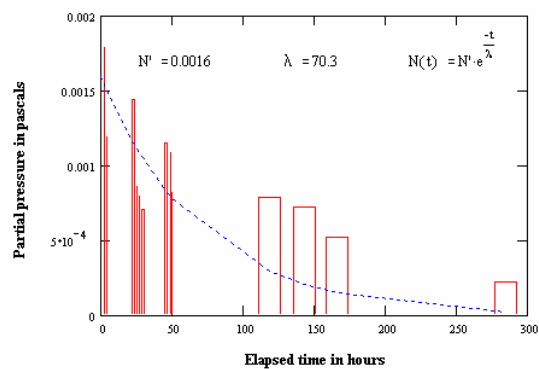


Figure 10: Partial pressure of H<sub>2</sub>O after 300 hours pumping in the vacuum chamber, no thermal cycling and temperature at 20° C.

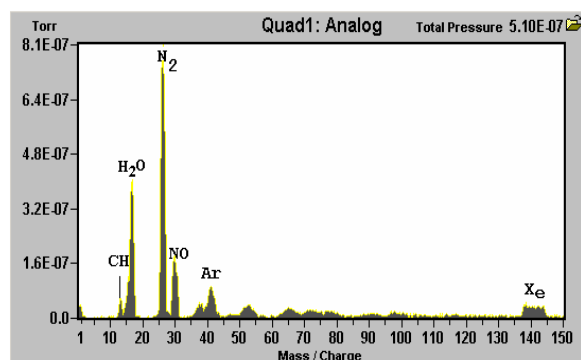


Figure 8: Trace shows the relative concentrations of various mass species after 5 complete thermal cycles. The trace was taken after array was cooled to 13° C.

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13. ABSTRACT (Maximum 200 words)  The purpose of the current work is to determine the out-gassing rate of H <sub>2</sub> O molecules for a solar array placed under daytime solar heating (full sunlight) conditions typically encountered in a Low Earth Orbital (LEO) environment. Arc rates are established for individual arrays held at 14 °C and are used as a baseline for future comparisons. Radiated thermal solar flux incident to the array is simulated by mounting a stainless steel panel equipped with resistive heating elements several centimeters behind the array. A thermal plot of the heater plate temperature and the array temperature as a function of heating time is then obtained. A mass spectrometer is used to record the levels of partial pressure of water vapor in the test chamber after each of the 5 heating/cooling cycles. Each of the heating cycles was set to time duration of 40 minutes to simulate the daytime solar heat flux to the array over a single orbit. Finally the array is cooled back to ambient temperature after 5 complete cycles and the arc rates of the solar arrays is retested. A comparison of the various data is presented with rather some unexpected results.				
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